

Experiment 3: Faraday Ice Pail

OBJECTIVES

1. To become familiar with the basic uses and capabilities of *Data Studio*.
2. To explore the charging of objects by friction and by contact.
3. To explore the charging of objects by electrostatic induction.
4. To explore the concept of electrostatic shielding.

INTRODUCTION

When a positively charged object such as a glass rod is placed near a conductor, electric fields inside the conductor exert forces on the free charge carriers in the conductor (electrons in metallic conductors), which cause them to move. Some of those negative charges redistribute themselves near the glass rod leaving the parts of the conductor furthest from the glass rod positively charged. This process occurs rapidly, and ends when there is no longer any electric field inside the conductor. The surface of the conductor ends up with regions where there is an excess of one type of charge over the other. This charge distribution is called an *induced charge distribution*. The process of separating positive from negative charges on a conductor by the presence of a charged object is called *electrostatic induction*.

Michael Faraday used a metal ice pail as a conducting object to study how charges distributed themselves when a charged object was brought inside the pail. Suppose the ice pail has a lid with a small opening through which we lower a positively charged metal ball into the pail *without touching it to the pail*. When we do this, negative charges in the pail move to the inner surface of the pail, because they are attracted to the positive charge on the metal ball, leaving positive charges on the outside of the pail. If we at this point touch our hand to the outside of the pail, those positive charges on the outside of the pail will run off to infinity through our hand. If we then remove our hand from the outside of the pail, and then remove the positively charged metal ball from the inside of the pail, the outside of the pail will be left with a net negative charge. This is called charging by induction.

In contrast, if we put the positively charged ball inside the uncharged pail and touch the inside of the ice pail, electrons flow into the ball, exactly neutralizing the positive charge on the ball. This leaves the pail with a net positive charge residing on the outer surface of the pail. This is called charging by contact.

Finally, when a positively charged ball approaches the ice pail from outside of the pail, charges will redistribute themselves on the outside surface of the pail and will exactly cancel the electric field inside the pail. This is called electrostatic shielding.

You will demonstrate all three of these phenomena—charging by induction, charging by contact, and electrostatic shielding—in this experiment.

We explain these phenomena in more detail in what follows. The fact that the excess charge on the ice pail resides entirely on the surface may be explained by Gauss's Law. Gauss's Law states that the electric flux through any closed surface is proportional to the charge enclosed inside that surface,

$$\oiint_{\text{closed surface}} \vec{E} \cdot d\vec{A} = \frac{q_{\text{enc}}}{\epsilon_0} . \quad (3.1)$$

The above relation describing Gauss's Law is Equation 4.2.5 of the 8.02 *Course Notes*; a more extensive explanation of the relation between Gauss's Law and Coulomb's Law may be found in Chapter 4 of the *Course Notes*.

Consider a mathematical, closed Gaussian surface that is *inside* the surface of the ice pail (Figure 1; think of this as a view of a thick-walled cylinder from above).

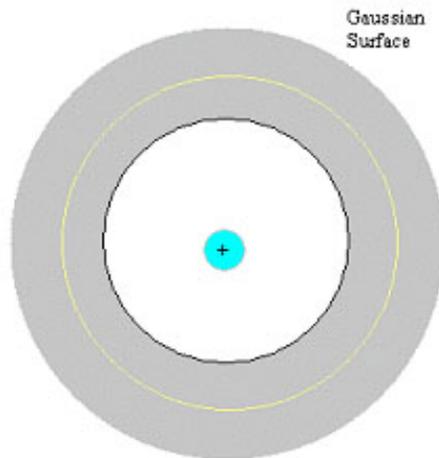


Figure 1 Gaussian surface for the Faraday Ice Pail.

Once static equilibrium has been reached, the electric field inside the metal walls of the ice pail is zero. Note that the electric field in the hollow region inside the ice pail is not zero due to the presence of the charged ball. Since the Gaussian surface is in a conducting region where there is zero electric field, the electric flux through the Gaussian surface is also zero. Therefore, by Gauss's Law, the net charge inside the Gaussian surface must be zero. For the Faraday ice pail, the positively charged ball is inside the Gaussian surface. Therefore, there must be an additional induced negative charge on the inner surface of the ice pail that exactly cancels the positive charge on the ball. Since the pail is uncharged,

by charge conservation, there must be a positive induced charge on the pail which has the same magnitude as the negative induced charge. This positive charge must reside outside the Gaussian surface, hence on the outer surface of the ice pail.

A further explanation of the nature of electric fields in and near a conductor may be found in Section 4.3 of the 8.02 *Course Notes*.

Now suppose the ice pail is connected to a large conducting object (“ground”) as in Figure 2:

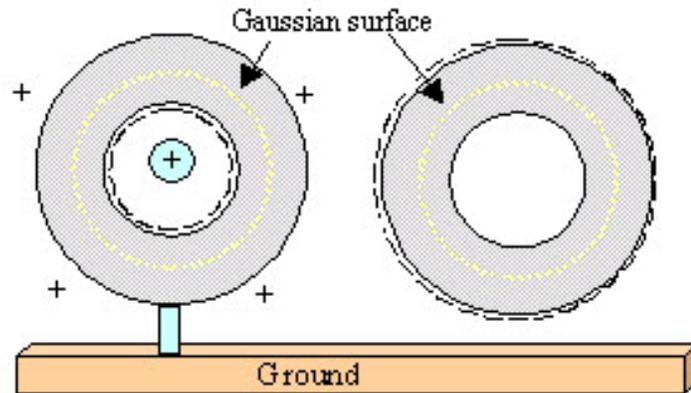


Figure 2 Charge distribution on the Gaussian surface.

When a positively charged object is inserted into the pail, negative charge carriers will flow from the ground onto the outer surface of the pail. If the wire to ground is then disconnected, the pail will have an overall negative charge. Once the positively charged ball is removed, this negative charge will redistribute itself over the surfaces of the pail; *i.e.*, the pail is charged negatively.

When a positively charged ball approaches the ice pail from outside of the pail, charges will redistribute themselves *on the outside surface* of the pail and will exactly cancel the electric field inside the pail. This effect is called shielding or “screening” and explains popular science demonstrations in which a person sits safely inside a cage while an enormous voltage is applied to the cage. This same effect explains why metal boxes are used to screen out undesirable electric fields from sensitive equipment.

APPARATUS

1. Ice Pail

Our primary apparatus consists of two wire-mesh cylinders. The inner cylinder (the “Ice Pail”) has a diameter of 10cm and is 15cm deep. Three insulating rods support the bottom of the inner wire cylinder above a plastic support stand. The outer wire mesh cylinder is also mounted on the support and acts as a screen to eliminate the effect of any

external charges and other external fields. The outer cylinder has no bottom wire mesh. It will be connected to a common ground; this means that electrons can flow to or from the shield as necessary.

We are making two approximations in this experiment. The wire mesh has many openings, so the actual induced charge distributions are quite complicated. Also, our “Ice Pail” does not have a lid, so technically there is no “inner” and “outer” surface on the inner wire mesh cylinder. Assume that the effects of these two complications are small and proceed as if our ice pail surface were solid and covered.

2. Charge Producer

In experiments using the Faraday “Ice Pail,” a charge producer (Figure 3) will be inserted inside the inner wire mesh cylinder. This will cause the inner wire mesh cylinder to develop an inner charge distribution and an outer charge distribution.

If the outer mesh is connected to ground, then the sign of the voltage on the inner wire mesh will have the same sign as the sign of the charge on the outer surface of the inner wire mesh. We will measure this outer charge distribution using a Charge Sensor.



Figure 3 Charge Producer

3. Charge Sensor

The Charge Sensor is a device that can detect charges on objects by measuring the voltage between them, as described below. The Charge Sensor has a very high input resistance, which means that it does not draw off significant amounts of charge. The Charge Sensor has two leads (Figure 4). The negative (black) lead of the Charge Sensor is connected to the outer wire shield, which acts as ground. The positive lead (red on the clip lead) is connected to the inner wire mesh cylinder.



Figure 4 Charge Sensor.

Your measurements will be primarily qualitative, so the following details about the Charge Sensor are mentioned only for general interest. The Charge Sensor actually measures the voltage difference between the inner wire mesh and the shield. This voltage arises from the charges on the outer surface of the inner wire mesh; positive voltage measurements correspond to positive charge on that surface. The voltage measurements can be converted into charge measurements by a calibration. The Charge Sensor is designed to minimally affect the actual charges on the inner wire mesh.

The Charge Sensor has a built-in amplifier with a gain G , which multiplies the measured voltage difference by a factor G to give an output voltage

$$V_{\text{out}} = G V_{\text{in}} \quad (3.2)$$

There are three gain settings: 1, 5 and 20 (Figure 5.) The amplifier can only read a maximum voltage input of $\pm 10\text{ V}$ on the 1x setting, $\pm 2\text{ V}$ on the 5x setting and $\pm 0.5\text{ V}$ on the 20x setting. The ZERO switch on the Charge Sensor brings the input voltage to ground.

Your amplifier should be set on the 1x setting.



Figure 5 Gain and Zero Settings for Charge Sensor.

When the Charge Sensor is used on the most sensitive range (20x), it may display a small “offset” voltage. That is, pressing the ZERO switch may not cause the voltage to go exactly to zero. Although this residual voltage is typically quite small (less than 0.1 volt), it will be constant for any particular gain setting and can be subtracted from the final measurement to give a more accurate reading.

EXPERIMENTAL SETUP



Figure 6 The *Science Workshop 750* Interface.

A. Charge Sensor and Calibration

1. Using the cable provided, connect the Charge Sensor to the Analog Channel A on the 750 Interface. The cable runs from the right end of the sensor as shown in Figure 5 to Channel A.
2. Connect the cable assembly on the BNC port on the Charge Sensor (see left end of the sensor in Figure 5). Line up the connector on the end of the cable with the pin on the BNC port. Push the connector onto the port and then twist the connector clockwise about one-quarter turn until it clicks into place.

3. Download the file The Charge Sensor **exp03.ds** from the web and save the file to your desktop (right click on the link and choose “Save Target As” to the desktop. Overwrite any file by this name that is already there). To start *Data Studio* with this file, either double click on this file or drag the icon for **exp03.ds** onto the *Data Studio* Icon on the desktop of the computer. Connect the Charge Sensor input lead (red alligator clip) to the inner wire mesh cylinder. The Charge Sensor ground lead (black alligator clip) attaches to the shield (the outer wire mesh cylinder). Set the Charge Sensor gain to 1x.

B. Data Studio File

The instructions presented here are quite basic; *Data Studio* is capable of doing much more, as we will see during the term. You are welcome to explore the possibilities as long as you complete this experiment. For instance, you might want to try to change the time duration of data recording to some other interval that suits you, or the ranges of your graphs or meters. The following instructions are for *Data Studio* as prepared in **exp03.ds**. For more information on how to use *Data Studio* for 8.02T, see the “Help” menu on the *Data Studio* toolbar.

1. The *Data Studio* file has a Voltage Graph and a Charge Graph.
2. The data recording is set at 10 samples per second (10 Hz), for a duration of 20 seconds.

MEASUREMENTS

Before starting any experiment using the Faraday Ice Pail, the pail must be momentarily grounded. **To ground the pail, touch both the inner wire mesh and the outer wire shield at the same time with a conductor such as the finger of one hand. You also will always want to always press the “ZERO” button on the Charge Sensor to discharge the sensor before starting.**

Each part of this experiment will require a bit of dexterity, and you might not get it right the first time or two. If so, this is of no consequence. Just try again as needed. For instance, if you accidentally touch the inside of the pail when you don't want to, you will need to try again.

Moving the Charge Producer carefully while watching two graphs is beyond the capabilities of most students. The data will be recorded on the graphs. One possibility is to have the members of a group rotate tasks.

Remember, the duration of data recording is set at 20 seconds, so you'll have to do what needs to be done in that time (or figure out how to change the recording duration, which

is not too hard). You might consider reversing the first two steps in each part (but be prepared to explain what effects this might have on your results).

Part 1: Polarity of the Charge Producers

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.
2. Start recording data. (The **start** button is located on the menu bar).
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Without touching the Ice Pail, lower the white Charge Producer into the Ice Pail. Watch the Graph displays.
 - Remove the white Charge Producer and then lower the blue Charge Producer into the Ice Pail. Watch the results.

Question 1 (answer on your tear-sheet at the end):

What are the polarities of the white and the blue Charge Producers? Note: There will be some variations in this, so if the neighboring group gets a different answer than what you get, that is ok.

Part 2: Charging By Contact Using the White Charge Producer

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.
2. Start recording data.
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Lower the white Charge Producer into the Ice Pail. Rub the surface of the white Charge Producer against the inner wire mesh cylinder and then remove the Charge Producer. Watch the Graph displays.

Question 2 (answer on your tear-sheet at the end):

What happens to the charge on the Ice Pail when you rub the inner pail with the white Charge Producer and then remove the Charge Producer?

Part 3: Charging By Contact Using the Blue Charge Producer

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.
2. Start recording data.
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Lower the blue Charge Producer into the Ice Pail. Rub the surface of the blue Charge Producer against the inner wire mesh cylinder and then remove the Charge Producer. Watch the Graph displays.

Question 3 (*answer on your tear-sheet at the end*):

What happens to the charge on the Ice Pail when you rub the inner pail with the blue Charge Producer and then remove the Charge Producer?

Part 4: Charging By Induction Using the White Charge Producer

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.
2. Start recording data.
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Lower the white Charge Producer into the Ice Pail, without touching the Ice Pail. While the Charge Producer is inside the pail, ground the Ice Pail. Once the Ice Pail is grounded and then isolated again, remove the white Charge Producer. Watch the Graph displays.

Question 4 (*answer on your tear-sheet at the end*):

What happens to the charge on the Ice Pail when you put the white Charge Producer in the Ice Pail without touching the Ice Pail, ground the pail briefly, and then remove the white Charge Producer?

Part 5: Charging By Induction Using the Blue Charge Producer

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.

2. Start recording data.
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Lower the blue Charge Producer into the Ice Pail, without touching the Ice Pail. While the Charge Producer is inside the pail, briefly ground the Ice Pail. Once the Ice Pail is grounded and then isolated again, remove the blue Charge Producer. Watch the Graph displays.

Question 5 (answer on your tear-sheet at the end):

What happens to the charge on the Ice Pail when you put the blue Charge Producer in the Ice Pail without touching the Ice Pail, ground the pail briefly, and then remove the blue Charge Producer?

Part 6: Testing the shield

1. Ground the Ice Pail and press the “ZERO” button on the Charge Sensor to discharge the sensor.
2. Start recording data.
3. Briskly rub the blue and white surfaces of the Charge Producers together several times.
 - Bring the white Charge Producer to *just outside the outer wire shield without touching the outer wire shield*. Watch the Graph displays.
4. After a few moments, stop recording data.
5. Repeat, bringing the blue Charge Producer just outside the shield.

Question 6 (answer on your tear-sheet at the end):

What happens to the charge on the Ice Pail when the white Charge Producer is placed just outside the outer wire mesh shield? Will an induced charge distribution appear on the inner wire mesh cylinder? Explain your reasoning. What about the blue Charge Producer?

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Physics

8.02

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Tear off this page and turn it in at the end of class.

Note:

Writing in the name of a student who is not present is a Committee on Discipline offense.

Experiment Summary 3: Faraday Ice Pail

Group and Section _____ (e.g. 10A, L02: Please Fill Out)

Names _____

Part 1: Polarity of the Charge Producers

Question 1:

What are the polarities of the white and the blue Charge Producers?

Answer:

Part 2: Charging By Contact Using the White Charge Producer

Question 2:

What happens to the charge on the Ice Pail when you rub the inner pail with the white Charge Producer and then remove the Charge Producer?

Answer:

Part 3: Charging By Contact Using the Blue Charge Producer

Question 3:

What happens to the charge on the Ice Pail when you rub the inner pail with the blue Charge Producer and then remove the Charge Producer?

Answer:

Part 4: Charging By Induction Using the White Charge Producer

Question 4:

What happens to the charge on the Ice Pail when you put the white Charge Producer in the Ice Pail without touching the Ice Pail, ground the pail briefly, and then remove the white Charge Producer?

Answer:

Part 5: Charging By Induction Using the Blue Charge Producer

Question 5:

What happens to the charge on the Ice Pail when you put the blue Charge Producer in the Ice Pail without touching the Ice Pail, ground the pail briefly, and then remove the blue Charge Producer?

Answer:

Part 6: Testing the shield

Question 6:

What happens to the charge on the Ice Pail when the white Charge Producer is placed just outside the outer wire mesh shield? Will an induced charge distribution appear on the inner wire mesh cylinder? Explain your reasoning. What about the blue Charge Producer?

Answer: